
Disks around Young Binary Stars

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Should this be an abstract?

1 Introduction

It is an observational fact that among young stars in many nearby star forming regions (SFRs) an excess binary population exists (e.g., [16, 25, 49]). This overabundance of doubles, in comparison to field stars in the solar neighborhood [14], correlates at least with the property of stellar density [43, 37, 35, 9]: the denser clusters contain a lower fraction of bound multiple systems. The maximum separation of bound systems is also related to the stellar density. [50] used a two-point correlation function to show that the transition between the binary and large-scale clustering regimes, and hence in the cutoff separation for the likelihood of a bound pair, increases from 400 AU (Orion Trapezium) to 5,000 AU (Ophiuchus) to 12,000 AU (Taurus), while the average stellar surface density decreases. Studies of large samples of binaries in very different star forming regions are key to unravelling the nature of binary formation mechanisms and the impact of environment on multiplicity fraction, distribution, and evolution.

The frequency and separation of young binary populations are perhaps most important when examined in light of the impact of companion stars on the potential for planet formation. Even for star forming regions in which the binary frequency is similar to that of the local field population, roughly two thirds of all member stars form in multiple systems. For a certain range of stellar separations, the presence of a companion star will clearly impact the formation, structure, and evolution of circumstellar disks, and, hence, of any potential planet formation. An insoluble problem among main-sequence field stars is the possibility of prior dynamical evolution of the system (e.g., [38]). The interactions between young stars and their associated circumstellar and circumbinary disks may set in motion this dynamical evolution. However,

examining these young systems in particular tells us about the initial *potential* for planet formation. Field star observations tell us if this potential was realized.

For very small separation binaries, models indicate that planet formation should be possible in a circumbinary disk (e.g., [45]). Several examples of close young binaries with circumbinary disks are well known, such as DQ Tau e.g., [29], UZ Tau E [41, 28], and HD 98800B [22, 40]. These pairs have separations of $\sim 30 R_{\odot}$ to 1 AU [8, 41, 11]. The GG Tau and UY Aur binaries, with stellar separations of tens of AU, are surrounded by angularly large and therefore well-studied circumbinary disks (e.g., [30, 13]). Recently, *Spitzer* observations of main-sequence pairs revealed debris disk material around 14 young stars with separations of several solar radii to ~ 5 AU [54]. However, in spite of these promising disk observations and model predictions, no planet has yet been detected orbiting a small separation, main-sequence binary (although a $2.4 M_{Jup}$ minimum mass planet orbits the G6V star HD 202206 and its $a=0.83$ AU substellar companion [55]). This dearth of detections may simply reflect the difficulties inherent in radial velocity (RV) searches for planets around binaries and the fact that binaries are typically eliminated from RV samples (e.g., [15, 23]).

Models also indicate a favorable outcome for planet formation in the circumstellar disks of binaries [46]. Reservoirs for this process, the optically thick, circumstellar disks around component stars, are routinely observed in binary systems with separations as small as ~ 14 AU (e.g., [17]). More than 30 extrasolar planets ($\sim 20\%$) have been reported around one component in binaries with separations of tens of AU up to thousands of AU ([15, 47]) — circumstellar planet formation seems to be common in multiple systems.

Necessary truncation of the outer portions of circumstellar disks in binaries with separations of a few to several 10's of AU likely delineates a planet-free zone. Interestingly, this fiducial separation is similar to that of the peak in the separation distribution for binaries in most SFRs (e.g., [35]). This "planet-free" regime of binary separation is also notably the least well-studied; components at such separations are too distant to be observed as spectroscopic binaries (orbital induced RV variations are on the order of star spot induced RV variations [48]), yet too close to be easily angularly resolved. Few data sets that go beyond initial binary identification exist, although there are some exceptions such as [17]. We therefore loosely define the binary separation regime most interesting, under-studied, and potentially treacherous to the formation and longevity of circumstellar disks, and therefore to the of formation of planets, as spanning a few AU to 30 AU. This definition is naturally modulo eccentricity and mass ratio, properties which could reinforce circumstellar disk destruction on short time scales.

In this paper, we will discuss the current state of observations of disks in young multiple systems with an emphasis on circumstellar structures. Disks in solar analogue and low-mass stellar systems will be primarily considered. The topics covered in this review are the evolution of inner disks in binaries (§2),

the evolution of outer disks in binaries and the determination of disk masses as derived from submillimeter astronomy (§3), the orientation of disks in binary systems (§4), and the structure of debris disks in young binaries (§5). We will present these topics through the lens of the potential for planet formation in these systems. In summary, §6 will present a discussion of future experiments and observations required to move knowledge in this field forward.

2 Inner Disks

Hydrogen emission line diagnostics ($H\alpha$ or $Br\gamma$) and near-infrared colors are effective determinants of weak-lined (no inner disk) and classical (optically thick inner disk) young stars (see [27, 39]). Substantial line emission and near-infrared excesses attest to the presence of gas and warm dust located in the inner ~ 2 AU of a circumstellar disk around a G – M spectral type young star. These disks are thought to evolve quickly from optically thick to thin states; few systems have been found in the intermediate “transition” state. The inner few AU of a circumstellar disk is the likely site of terrestrial planet formation and thus is particularly important.

Monin et al. (2007) classified a sample of young binaries with separations of $\sim 15 - 1500$ AU on the basis of these diagnostics. In an extensive search of the young star binary literature, only ~ 60 systems were found for which both component spectral types were known and for which angularly resolved $H\alpha$, $Br\gamma$, K–L, or K–N ($K=2.2\mu\text{m}$, $L=3.4\mu\text{m}$, and $N=10\mu\text{m}$) color data were available. These few dozen systems are drawn from a variety of star forming regions, and thus do not represent a homogeneous sample. This dramatically underscores the unavoidable small number statistics inherent in any analysis of this sample, and the pressing need for a substantial observational effort in this area.

In spite of the small sample size, [33]’s analysis revealed intriguing results and trends (Figure 1). One surprising and relatively robust outcome is that mixed pairs, in which the components appear to be in different evolutionary stages, are not as rare as once believed (e.g., [39, 17]), comprising approximately 40% of the sample. Less statistically notable are the suggestions that these systems are more common among the larger separation pairs and that a slight majority these systems are detected among the lower mass ratio pairs. There is also a hint in the available data that the frequency of mixed pairs may vary between star forming regions. Unfortunately, because of the sparse data, these results are all at the 2σ level at best.

Angularly resolved high-resolution spectroscopy of close young binaries yields insight into either the alignment of stellar orbital axes, or discrepant rotation rates. This degeneracy can be resolved with a time series observations designed to obtain component stellar rotation periods. If rotation axes are aligned, discrepant rotation periods would suggest star-disk locking in only one component. What regulates such discrepancies in double star systems that

presumably form and evolve together in the same relative environment? Determination of the stellar properties favorable to long-lived inner disks bears directly on the question of what kind of stars are most likely to host planets. Figure 1 shows a young binary with component $v\sin i$'s discrepant by a factor of 2–3. Intriguingly, this ~ 700 AU separation Ophiuchus binary, an M3 and an M7, is a mixed system (e.g., [42]). The rapidly rotating primary is not associated with dusty circumstellar material, however, the low mass companion is [31], as we might expect from a disk-locking scenario. Similar discrepancies have also been observed in a 30 AU separation young binary in Taurus (results in preparation for publication).

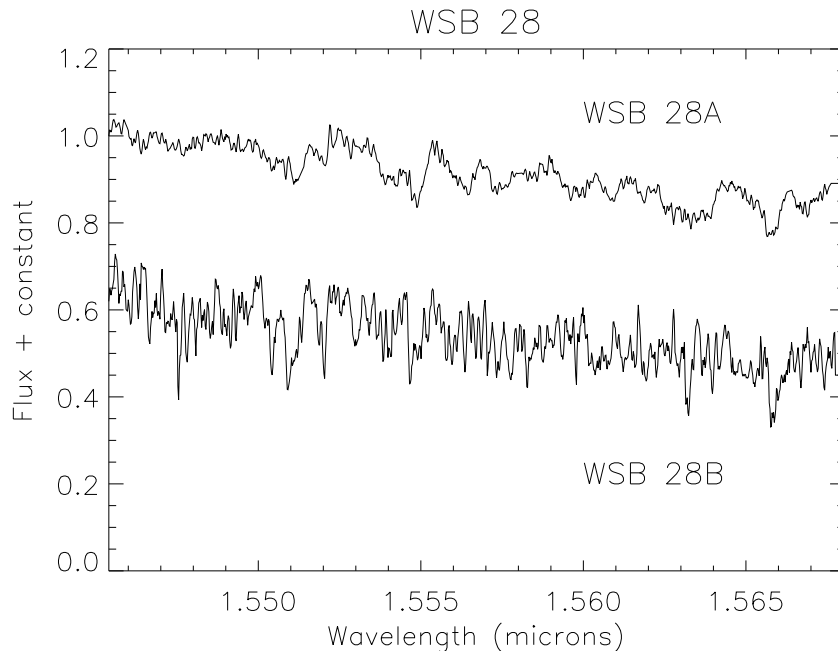


Fig. 1. R=30,000 spectra of the components in the young binary WSB 28. The $v\sin i$'s are discrepant by a factor of 2–3, indicating either unaligned rotation axes or significantly different rotation periods. Veiling from circumstellar material cannot account for the shallow features in the M3 primary because this component is not associated with any circumstellar material, although the M7 secondary is [31]).

How much of an impact might selection effects have on the results presented here? Certainly small mass ratio systems are more difficult to detect as well as to characterize, particularly in the most interesting small separation regime (§1). Systems classified as weak-lined T Tauris, unresolved, might also harbor truncated disks around the secondary stars. Such small structures

could go undetected as the result of dilution from a relatively bright primary. Circumstellar disks with central holes that show excesses in the mid-infrared but not in the near-infrared, and which do not show signatures of accretion, may be present but are effectively undetectable. Even if sensitive but low-angular resolution *Spitzer* observations could reveal the presence of such a structure, there is little recourse for ground-based mid-infrared follow up at sufficiently high sensitivity and angular resolution. Only 4 of the circumstellar disks in the young binary sample of [31] (TTau N and S, UZ Tau E, and RW Aur A) are brighter than the N=4 mag limit of the VLTI mid-infrared instrument MIDI.

We must also take into account that the completeness of our knowledge of binary populations varies markedly between different star forming regions, possibly leading to an inaccurate determination of differences in mixed pair fractions, etc, between regions. Taurus, given its small size and ready accessibility in the northern skies, is arguably the most thoroughly studied region. However, its faintest members are only now being surveyed for multiplicity [24].

3 Outer Disks

The cool gas and dust in outer disks, including circumbinary disks, is best surveyed using far-infrared or submillimeter observations. Disks are usually optically thin at long wavelengths, so these observations have the additional benefit of providing total disk masses (e.g. [2]) in the region analogous to where giant planets formed in the Solar System.

Although estimates of the binary fraction were highly incomplete when the first submillimeter surveys were done, it was still clear immediately that binary stars with separations closer than 100 AU were deficient in disks [18, 34]. In recent work, a survey of 150 young stars in Taurus including 62 multiple stars showed lower submillimeter fluxes and hence masses in systems closer than ~ 100 AU than in single stars, while wide binaries were similar to single stars in disk mass [3]. Disks were present, albeit at these lower masses, in approximately the same fraction of multiple star as single star systems. Perhaps these disks can still form giant planets, but of lower average mass, than the single stars.

Models of disk dissipation generally show that the circumsecondary disk, which should be truncated closer to the star due to the primary, should dissipate faster [5]. In single stars, disk mass is not correlated with stellar mass [3], so it is quite possible for circumsecondary disks to start out as more massive than circumprimary disks, and these initial conditions can overwhelm the difference in dissipation timescale.

The surveys described above were carried out with single dish telescopes and therefore have low spatial resolution incapable of distinguishing primary and secondary disks at the interesting separation range of $< \sim 100$ AU. A

smaller number of objects have been surveyed with interferometers that can resolve the multiple systems. In one such survey, the primary stars of four binaries in Ophiuchus hosted higher mass disks, even when the secondaries were still accreting, while in four binaries in Taurus the circumsecondary disks were more massive [36]. In these very young objects, the true “primary” may have been misidentified in extincted visual-wavelength data, or these trends may relate to the initial conditions. For four wider systems, also in Taurus, the circumprimary disks were again the most massive (and again comparable to single stars in Taurus) [20].

4 Orientation of Disks in Young Binaries

A single star plus disk system contains a single plane: that of the disk. A binary system, however, is associated with four relevant planes: a circumstellar disk around each star, the plane of the binary orbit, and the plane of any circumbinary disk, although the latter are relatively rare [19]. *Alignment* of circumstellar disks does not necessarily imply coplanarity of the binary orbital plane with that of the aligned disks (Figure 2). The polarization studies of [21] and [32] trace circumstellar alignment, for relatively wide, angularly resolved young binaries, using the orientation of the polarization position angles of dust grains in the disks. They found that most simple binary systems studied exhibit aligned disks with polarization position angles consistent to within <30 degrees, although higher order multiples show a large range of variation in polarization position angles.

The orientations of the highly collimated jets that emanate from many young star systems provide a proxy for determining disk orientations in unresolved binaries as jets are thought to launch perpendicular to the inner circumstellar disks. Multiple misaligned jets are known to exist in a number of young systems (e.g., [33] and references therein), suggesting that it is possible for small separation binaries to actually *form* with misaligned disks (Figure 2, case c). Thus, formation models must account for this counterintuitive evidence.

The coplanarity of disks and binary orbits is readily studied for some well-separated pairs. Interestingly, it appears likely that circumbinary disks are aligned with close binary star orbits, e.g., for DQ Tau, UZ Tau E, and HD 98800 B [29, 41, 40]. However, systems with a circumstellar disk around at least one component of a wider binary, e.g., HV Tau AB-C, HK Tau A-B, UZ Tau E-W, T Tau N-S, and HD 98800 N-S [52, 51, 41, 1, 40], *do not* appear to be coplanar. The dynamics of circumbinary and even close circumstellar disks and the interrelationship between disks and orbits appears to be complex and is not yet well understood. We present these conclusions as a cautionary tale: even binaries with separations of a few tens of AU – or less – cannot be assumed to harbor aligned disks coplanar with binary orbits. In higher order multiples, misalignments may be the rule. It is likely that in at least some

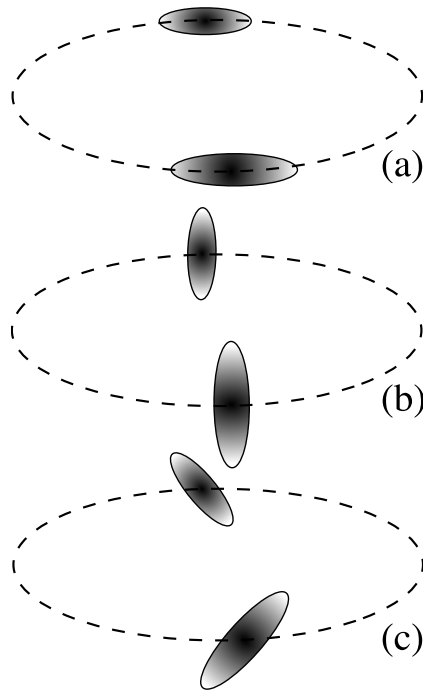


Fig. 2. Circumstellar disks in a simple binary orbit: (a) aligned and coplanar, (b) aligned but non-coplanar, (c) unaligned and non-coplanar.

cases misalignment may have its origins in the formation dynamics of these systems.

5 Debris Disks and Binaries

There are several well studied examples of binary systems amongst the older class of circumstellar disks – the transitional and debris systems. These are disks in which the primordial material, particularly gas, is partially or totally dissipated and remaining solids are large enough that their major destruction mechanism is collisions (either aggregation onto planets or disruptive). Giant planets must either have already formed in these systems or will not and terrestrial planets may be in their final stages of accumulation, perhaps eras akin to the late heavy bombardment in the solar system. These systems are closer to the Sun than the nearest sites of recent/ongoing star formation discussed earlier, so the affect of binarity on the disks can be observed in some detail. We will discuss two examples.

HD 141569 is a hierarchical triple star system consisting of an A0-type primary star, which sports an extended disk containing both small quantities

of gas and dust, and two M-type companion stars located about 1000 AU away. The low mass stars, and presumably the whole system, are about 5 Myr old [57]. Spiral structure at 200–500 AU in the primary’s disk can be explained by either a highly eccentric ($e > \sim 0.7$) binary A-BC orbit [7, 44, 4] or a recent (~ 1000 yr ago) stellar flyby [10]. In both cases, the portion of the disk affected by the companions is at distances of a few hundred AU, and structure in the disk at < 150 AU must have another cause, perhaps a planet. Interestingly, the two M-type stars have no detectable disks below the level seen around the primary star. This could be due to the small separation of their orbit, ~ 150 AU.

HD 98800 is a member of the ~ 8 Myr old TW Hya Association and is composed of four nearly identical stars in two spectroscopic binaries. All of the dust encircles one of these pairs, HD 98800Bb [26, 22, 40]. Thus, the system has characteristics of both a circumbinary and circumstellar disk. The Bb binary is eccentric ($e=0.78$) with a semi-major axis of 1 AU [11]. Based on its temperature, the inner edge of the dust disk sits at 1.2 – 2.1 AU (Prato et al.). This is just barely consistent with estimates of the dynamical tidal truncation [6]. The A-B orbit is also significantly eccentric (0.3–0.6) with a periastron approach of perhaps 35 AU [53]. The outer edge of the dust disk is less well constrained by the infrared/submillimeter observations, but is > 5 AU and could be as large as 25 AU [22]. An outer size of 10 AU would fit both the observations of the dust temperature and the expected dynamical truncation due to the A-B orbit.

While both of these systems provide interesting examples of the dynamical influence of multiplicity on the disk, they also illustrate that planet formation is possible under such complicated circumstances. The small dust grains in the HD 141569A and HD 98800B disks are regenerated in collisions [56, 7, 26] and indicate that planetesimals did form on timescales short enough that gas could have been present simultaneously with solid bodies..

Statistics of the incidence of debris disks around binaries are consistent with the idea that wide binaries do not affect disk evolution. A survey of 69 FGK stars including binaries of separations > 500 AU finds 3/8 of the disks are around binary members [12].

6 Future Tests and Observations

A tremendous observational effort is required to explore the most populous binary separation regime, and that of most scientific interest with respect to planet formation — a few to ~ 30 AU separations.

Ongoing spatially resolved spectroscopy with adaptive optics systems on large telescopes will assess the accretion parameters and inner disk optical depths of circumstellar disks in close binaries. With concerted observational attention, it seems a solvable problem to measure the dissipation timescales of primary and secondary disks. Ground based interferometers will get detailed

orbits for close binaries which can then be compared to disk sizes for empirical verification of dynamical estimates of tidal disruption and dissipation.

One big advance will come with operation of the Atacama Large Millimeter Array (ALMA). With its sub-arcsecond resolution, comparable to that of Hubble Space Telescope, it will be able to determine the masses and orientations of the circumstellar disks in binary systems at the critical separation range.

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